U.S. DEPARTMENT OF COMMERCE
National Technical Information Service

AD-A030 967

Advances in Engine Burst Containment and Finite Element Applications to Battle-Damaged Structure

Advisory Group for Aerospace Research & Development Paris France

Sep 76

96066

AD A030567

AGARD-R-648

AGARD-R-648

AGARD

ADVISORY GROUP FOR AEROSPACE RESEARCH & DEVELOPMENT

AGARD REPORT No. 648

on

Advances in Engine Burst Containment and Finite Element Applications to Battle-Damaged Structure

NORTH ATLANTIC TREATY ORGANIZATION

DISTRIBUTION AND AVAILABILITY
ON BACK COVER

AGARD-R-648

NORTH ATLANTIC TREATY ORGANIZATION

ADVISORY GROUP FOR AEROSPACE RESEARCH AND DEVELOPMENT

(ORGANISATION DU TRAITE DE L'ATLANTIQUE NORD)

AGARD Report No.648

ADVANCES IN ENGINE BURST CONTAINMENT AND FINITE ELEMENT APPLICATIONS TO BATTLE-DAMAGED STRUCTURE

A

Papers presented at the 42nd Structures and Materials Panel Meeting, Ottawa, April 1976.

THE MISSION OF AGARD

The mission of AGARD is to bring together the leading personalities of the NATO nations in the fields of science and technology relating to aerospace for the following purposes:

- Exchanging of scientific and technical information;

- Continuously stimulating advances in the aerospace sciences relevant to strengthening the common defence posture;

- Improving the co-operation among member nations in aerospace research and development;

- Providing scientific and technical advice and assistance to the North Atlantic Military Committee in the field of aerospace research and development;

- Rendering scientific and technical assistance, as requested, to other NATO bodies and to member nations in connection with research and development problems in the aerospace field;

- Providing assistance to member nations for the purpose of increasing their scientific and technical potential;

- Recommending effective ways for the member nations to use their research and development capabilities for the common benefit of the NATO community.

The highest authority within AGARD is the National Delegates Board consisting of officially appointed senior representatives from each member nation. The mission of AGARD is carried out through the Panels which are composed of experts appointed by the National Delegates, the Consultant and Exchange Program and the Aerospace Applications Studies Program. The results of AGARD work are reported to the member nations and the NATO Authorities through the AGARD series of publications of which this is one.

Participation in AGARD activities is by invitation only and is normally limited to citizens of the NATO nations.

Published September 1976

ISBN 92-835-1224-3

Printed by Technical Editing and Reproduction Ltd
Harford House, 7-9 Charlotte St, London W1P 1HD

REPORT DOCUMENTATION PAGE

1. Recipient's Reference	2. Originator's Reference	3. Further Reference	4. Security Classification of Document
	AGARD-R-648	ISBN 92-835-1224-3	UNCLASSIFIED

5. Originator	Advisory Group for Aerospace Research and Development North Atlantic Treaty Organization 7 rue Ancelle, 92200 Neuilly sur Seine, France
6. Title	ADVANCES IN ENGINE BURST CONTAINMENT AND FINITE ELEMENT APPLICATIONS TO BATTLE-DAMAGED STRUCTURE
7. Presented at	the 42nd Structures and Materials Panel Meeting, Ottawa, April 1976.

8. Author(s)	9. Date
Various	September 1976

10. Author's Address	11. Pages
Various	22

12. Distribution Statement	This document is distributed in accordance with AGARD policies and regulations, which are outlined on the Outside Back Covers of all AGARD publications.

13. Keywords/Descriptors

Damage	Bursting	Structural analysis
Aircraft	Impact strength	Containment
Aircraft engines	Weapons effects	

14. Abstract

Aircraft must be designed to sustain damage arising from the impact of a variety of types of projectiles such as military weapons and debris from engine disintegration. Recognising the need for the collection and dissemination of information on this topic, the AGARD Structures and Materials Panel has set up a Working Group on the Impact Damage Tolerance of Structures charged with the task of producing a Design Manual. A specialist meeting was held in Ankara, Turkey in September 1975 and the conference proceedings have been published as AGARD-CP-186.

Two further papers were presented to a private session of the Working Group in April 1976. The paper by Messrs. Bristow, Davidson and Gerstle reviews some recent research into the application of fragment impact studies to an understanding of engine burst fragment impacts and the initial development of an engine burst containment system. The paper by Dr Huang described a method of analysis of a battle-damaged structure using the NASTRAN structural analysis program supplemented by preprocessors designed to automatically generate input data; a "patching technique" is then used in the development of a finite element model truly representing a battle-damaged structure.

PRICES SUBJECT TO CHANGE

PREFACE

Aircraft must be designed to sustain damage arising from the impact of a variety of types of projectiles such as military weapons and debris from engine disintegration. Recognising the need for the collection and dissemination of information on this topic, the AGARD Structures and Materials Panel has set up a Working Group on the Impact Damage Tolerance of Structures charged with the task of producing a Design Manual. To stimulate the collection of data a specialist meeting was held in Ankara, Turkey in September 1975 and the conference proceedings have been published as AGARD-CP-186.

Two further papers, which became available too late to be presented at this meeting, were presented to a private session of the Working Group in April 1976. These were well received by the audience at this session; it was considered that they would be of immediate value to those concerned with the problem of impact damage tolerance and therefore this AGARD Report has been published to give them wider circulation.

The paper by Messrs. R.J.Bristow, C.D.Davidson and J.H.Gerstle on "Advances in Engine Burst Containment" reviews some recent research into the application of fragment impact studies to an understanding of engine burst fragment impacts and the initial development of an engine burst containment system. The paper by Dr. Pao. C Huang on "Finite Element Applications to Battle-Damaged Structure" describes a method of analysis of a battle-damaged structure using the NASTRAN structural analysis program supplemented by preprocessors designed to automatically generate input data; a "patching technique" is then used in the development of a finite element model truly representing a battle-damaged structure.

N.F.HARPUR.
Chairman, Working Group on
Impact Damage Tolerance of Structures

CONTENTS

ADVANCES IN ENGINE BURST CONTAINMENT

by

R. J. Bristow, C. D. Davidson and J. H. Gerstle
Senior Engineers
P.O. Box 3999
Seattle, Washington 98124
USA

SUMMARY

This paper presents a partial review of recent research by The Boeing Company into the application of fragment impact studies to an understanding of engine burst fragment impacts and the initial development of an engine burst containment system using duPont Kevlar material. All test work to date has involved translational accelerators but spin pit testing is planned for the near future. The program has not yet resulted in a satisfactory containment system. However, it is hoped that the basic data accumulated will provide the building blocks in the development of design criteria for such a system.

In addition to a summary of program accomplishments, this paper delves into several areas where unexpected results occurred and where information was obtained that may influence future fragment containment efforts. One of these areas involves spinning fragments. None of the predicted adverse effects on Kevlar fabric were found. Another area concerns thermal effects. It was found that the efficiency of the barrier in stopping fragments was influenced by the temperature of the Kevlar.

INTRODUCTION

Since the early 1960's, a group at Boeing has been involved in the study of impact phenomenology and means to control the resulting damage. These studies have ranged from meteoroid protection with test velocities of up to 32,000 fps down to free-falling rocks with test velocities as low as 10 fps. During this period, many shielding concepts were developed. The usual method was to perform a number of parametric tests, describe the damage (or other parameter of interest) in terms of a mathematical model involving projectile, target, intercept and environmental characteristics. The resulting model was then used to optimize the shield design or to develop design criteria.

Lightweight shields were found to require two properties: shear resistance locally around the impact point and tensile strength to bring the fragment to a stop after the initial impact. It was also noted that both tensile and shear strength requirements could be reduced by using a shield material with good elasticity. Keeping these requirements in mind, blast container weights were reduced by substituting fiberglass fabric for the normal steel shield material. (Elasticity was increased by designing the overall container to "give" locally.) While the fiberglass was found to be very efficient for containing blast waves and residual gases, its poor bending and cut resistance made it unsuitable for containing fragments. Nylon was found to have good small fragment stopping ability, but lacked the tensile strength required to contain blast waves or large fragments.

Currently, a new fabric is being investigated. This new fabric, called "Kevlar" by its manufacturer, duPont, is receiving wide publicity and appears destined to find a number of military and commercial applications. The purpose of this paper is to summarize the results of Boeing's study of the ability of Kevlar to stop fragments. Potential uses of resulting shields would be to protect explosive storage tanks, to contain fragments from burst electrical power generating turbines in stationary nuclear power plants, and for use as shields against the blast and fragments of HE warheads. Of particular interest to AGARD would be the use of Kevlar shields around jet engines to contain fragments in the case of an engine burst due to battle damage. The sizes and shapes of fragments are quite variable depending on the type of engine and the failure mode. Types of disc failure modes are shown in Figure 1. Figure 2 is a photo of some of the resulting fragments.

BACKGROUND

In 1966, Boeing carried out ballistic containment tests on titanium to provide localized shielding on the Boeing 737. In 1971, tests were initiated to find a woven roving fiberglass configuration to protect a helicopter fuselage from engine blade failures. The woven roving shields were retained until the engine manufacturer rectified the blade weakness. In 1972, the concept of a lightweight flexible energy absorbing barrier utilizing a fabric was conceived. The concept was for the barrier to perform in a manner similar to a net, giving on impact and then absorbing the energy in tensile loading of the fibers. A series of ballistic impact tests was carried out on "S" glass fabric shields and while the results were encouraging, they were inconsistent. This inconsistency was due to the susceptibility of the monofilament glass to handling damage and the poor cut resistant properties of the filaments.

As a result of a material search, the duPont material Kevlar was proposed since it showed good mechanical properties (Table 1). The majority of Boeing activity since has been based on Kevlar material, and this paper primarily deals with work done in the containment field with this aramid fiber.

Shield Design Approach

Many ballistic barriers have been developed in the past. However, these developments have generally involved solid barrier materials. By using flexible fabric materials, a number of additional variables were introduced; type of weave, fabric stretch, layer interactions, restraint of individual fibers around the barrier periphery. To investigate all of these variables in a spin pit would be economically prohibitive. For this reason, it was planned that the majority of the development work would be conducted in a ballistic impact laboratory and that development would proceed along lines established for solid barriers. In addition to economics, the ballistic lab approach had the advantages of greater control over fragment sizes, velocities and impact angles.

In the impact laboratory, the many containment shield configurations could be reduced to the best two or three which could then be spin pit tested. The spin pit would only be used to validate and confirm the laboratory results and to impart to the fragment a realistic rotational velocity.

The early shield designs were corrugated with variation in the depth and spaceing of the corrugations. A face plate of .028 CRES sheet was provided and the corrugations were held in position by wire. Flat shields were also designed of Kevlar and impact tested. The containment performance of this flat shield when based on a weight per unit area was found to be equally effective to the corrugated type shield. Since the flat shield was less costly to manufacture and, also, had installational advantages, the remainder of the recent shield development program was based on the flat design configuration. The other variables that were investigated included varying the shield weight, the material weave, the effects of Kevlar ballistic felt and the effect of locating acoustic lining behind the shield. In addition, barriers were tested with matrix around the Kevlar such that the barrier could replace some of the existing structure. Altogether, there were over 20 different shield design configurations.

Test Equipment

The layout of the impact test facility which is shown schematically in Figure 3 and by photo in Figure 4 was used for the shield testing; it consisted of a 2.5 or 6 in. diameter bore launching barrel, 60 in. long, with a threaded-on breach. The projectile to be launched (Figure 5) was placed in a sabot assembly and loaded into the barrel. The impact velocity was varied by the weight and type of powder charge. The launcher muzzle extended into a plenum where the burned gases were vented and a trap was incorporated to restrain the sabot halves. As the projectile traveled downrange, it passed through two printed electrical circuit sheets, spaced two feet apart, triggering the circuit of the electronic velocity analyzer. The impact chamber had a movable steel cover with an acrylic window to provide access for mounting of the shields and viewing ports for photography. The projectile travel from muzzle to shield was approximately 10.0 ft.

The residual velocity of the projectile was measured by the number of witness sheets penetrated, (Figure 6 shows witness sheets and a "flat" shield mounted on its support bracket).

A metal block was used to simulate the fragment and was varied from a 3/4 in. to 3 in. cube with variations such as changing the aspect ratio (1 x 1 x 3) and changing its density by using different materials. The reasons for using a cube were that it has a cutting edge which would more represent engine fragments than a sphere, is easy to manufacture, and is inexpensive. It's size can be varied easily to represent different size fragments. Also, the compact shape of the cube resulted in reasonably consistent test data. It was the intent to impact the shield at energy levels and velocities which would be expected from an engine, e.g., no blade velocities in excess of 1200 fps and no blade root velocity greater than 900 fps.

Test Results

Figure 7 shows the containment performance of Kevlar shields for two projectile sizes, plotting shield weights (uninstalled) against contained energy. Also shown are the containment energy levels for other materials from tests done previously by other agencies and Boeing. These results reflect the flat shield configuration. It was established that the corrugated type shield and the varying types of material weave showed no advantage. A ballistic felt-faced shield showed about 5% improvement which is within the data scatter. The placing of acoustic lining material (either polyimide or aluminum) behind the shield showed no significant change in containment performance.

Empirical Model

Empirical and semi-empirical models have been developed in the past for many types of impact phenomena; armor plate, structural damage, meteoroid impact, and hail to mention only a few. These models have been found to be extremely useful in designing and optimizing hardware associated with the phenomena. For this reason, an empirical model was developed to represent the laboratory containment barrier data.

The basic barrier test data was first plotted as a function of a barrier layer and witness sheet penetration as shown in Figure 8. (The witness sheets were a set of 1/16 inch aluminum plates placed behind the test barrier. Enough plates were used to assure that the cube projectile would stop somewhere in the set.) The point where the typical "S" shaped curve crosses the boundary between barrier and witness sheet penetration is the ballistic limit (incipient penetration completely through the barrier).

An empirical model was then developed to express the ballistic limit as a function of several of the most important variables; fragment size, velocity, impact angle and number of layers of Kevlar. The resulting model was:

$$W = AV^2 D^{3/4} (\sin\theta)^{5/6} - B$$

where W = areal density of Kevlar - lb/ft^2

= 0.067 N, N = number of Kevlar layers ($9.6\ oz/yd^2$ fabric)

V = impact velocity at ballistic limit - fps

D = cube size - inches

θ = impact angle measured from cube flight path to barrier surface

A & B - Constants

In order to make the model more usable, the nomogram of Figure 9 was developed. Knowing the fragment size, velocity and impacting angle, the Figure 9 nomogram makes it very easy to determine the number of Kevlar layers required to stop the fragment.

Once a model such as the one above has been developed, it is useful to examine the variables in detail. The barrier weight is seen to depend on the square of the velocity of the fragment. This appears reasonable since the fragment kinetic energy depends on the square of the velocity. However, the model shows that the dependency on fragment size is only the 3/4 power of the cube dimension. This would indicate a dependence on mass of only mass to the 1/4 power. In other words, the barrier weight is not strongly dependent on fragment mass. An increase in fragment mass by a factor of 16 would require a barrier weight increase of only two.

Spinning Fragments

When an engine bursts the resulting fragments have both linear and rotational energy components. The ratio of these types of energy varies from all rotational for a complete disc to virtually all linear for a small rim fragment. It has long been felt by some investigators that the fragment spin responsible for the rotational energy would severely limit the usefulness of fabric barriers. They theorized that the rapidly spinning fragment would act like a "buzz saw" to cut through the fibers.

In order to determine if spin would indeed cause the fragment to saw through the barrier, a test series was set up in which the projectile was made to spin before hitting the barrier. This was accomplished by placing a 5" wooden ramp in front of the barrier. Upon hitting the ramp, the edges of the cube projectile dug into the wood and caused the projectile to roll up the ramp. The resulting spin rate was deduced from high-speed motion pictures (normally 10,000 frames per second). Figure 10 shows the results of some of the testing. Considerable scatter is shown. However, with spin rates varying from 9000 to 24,000 RPM, no degradation in barrier efficiency was found.

In a completely different type of test, some of the effects of spinning projectiles were also noted. In this test series, the effects of projectile geometry were being studied. The cube projectiles were replaced by rods one by one by two or three inches long, fired end-ways into the target as shown in Figure 11. This rotation was, in effect, a high speed spin by the time the rod stopped, as shown in Figure 11.

The conclusion to be drawn from these tests, and to be later verified in a spin pit, is that spin has little, if any, detrimental effect on the ability of a fabric barrier to stop fragments.

Temperature Effects

In an actual installation, the engine containment barrier will experience a range of temperatures. The effect of these variations under static conditions was known from work done by duPont (Figure 12). This work indicated that Kevlar properties were constant until a certain temperature is reached and then fall off gradually at higher temperatures. It was decided to conduct a test to make sure that the barrier would function properly at the highest temperature anticipated, 320°F. The results were surprising. Instead of getting a slightly reduced ballistic limit as expected, the Kevlar material appeared to have better properties at higher temperatures. The high temperature tests were expanded and included some at cold temperatures. The results were as shown in Figure 13. Above room temperature, the ballistic limit steadily improved up to about 420°F. Above this temperature, the efficiency of the barrier rapidly fell off.

It was surmised that the increasing ballistic limit with temperature was due to strain rate effects; that strain rate effects increased faster with temperature than the static strength decreased. In order to test this theory, a variable speed tensile test machine was used to determine the properties of Kevlar at different temperatures. The machine was capable of strain rates from 0.05 to 18.5 in/in/min. The results are shown in Figure 14. Strain rate effects do indeed appear to be indicated.

Considerable more study is required, but it appears that the variation in ballistic limit with temperature may be used to advantage in the design of barriers. However, it appears that temperature cycling reduces the Kevlar properties in some as yet unknown manner. Figure 15 shows tests wherein test specimens were cycled various numbers of times prior to test. In all cases the capability of the barrier was reduced. As shown in the figure, few cycling data points are available, hence there is much uncertainty as to the overall effects of temperature cycling.

FUTURE PLANS

The end objective of our work at Boeing is to understand design criteria for a lightweight engine burst containment shield. Present effort focuses on three areas; increased energy containment, attachment design, and spin pit verification of laboratory impact testing.

The manner in which the barrier is attached to the aircraft (or to itself) is closely related to installation design problems. However, it is also important for the development of the barrier itself. It has been found that as the size of the fragment goes up, the greater is the dependency of the ballistic limit on the method of attachment.

All testing to date has been with translational accelerators only. This year the plan is to verify these results in a spin pit. A disc with blades will be made to separate into three or four segments. These segments will then impact a barrier which is designed on the basis of translational tests.

CONCLUSIONS

Progress has been made in the development of technology for engine burst containment. However, a number of major problems must be solved before a barrier of this weight can be placed in an aircraft. These problems include practical attachment concepts, temperature cycling degradation, and the extrapolation of current containment designs to the higher energy levels.

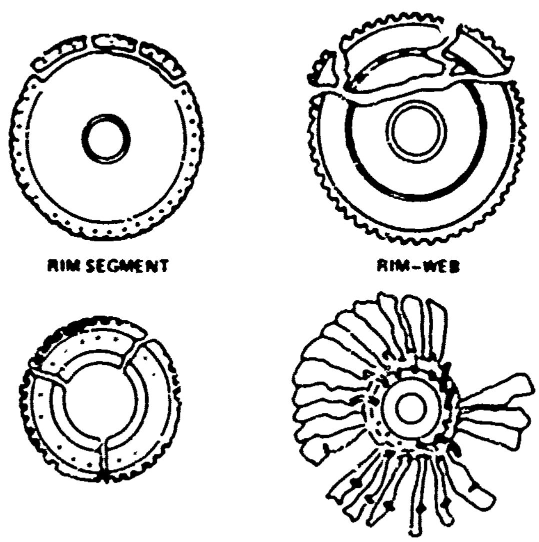
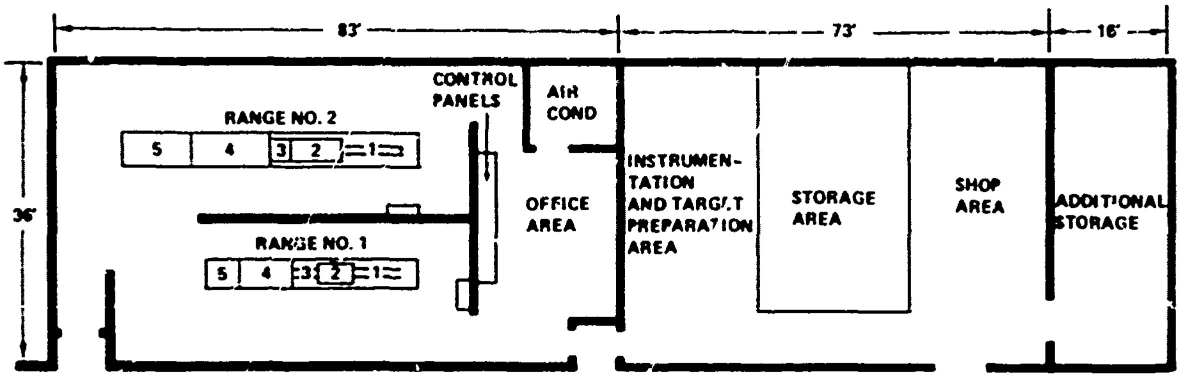


Figure 1 Disc Failure Modes –

Figure 2. Engine Burst Fragments

Table 1. Engine Burst Containment Material Properties

	TITANIUM 6AL-4V	CONTINUOUS FILAMENT "S" GLASS	CONTINUOUS FILAMENT-SYNTHETIC KEVLAR 29
TENSILE STRENGTH (PSI) FILAMENT	—	600,000	400,000
FABRIC	157,000	324,000	300,000
WEIGHT RATIO	1.74	1.0	0.50
LOOP STRENGTH (PSI)—FILAMENT (CUT RESISTANCE)	—	NEGLIGIBLE	240,000
TEMPERATURE RESISTANCE (PSI)	127,000 AT 400° F	SIZING BURNS OFF ABOVE 350° F LEAVING GLASS EXPOSED AND SUBJECT TO ABRASION	FILAMENT 316,000 AT 300° F (320° F MAX FOR CONTINUOUS USE)



1. LAUNCHER POSITION
2. PLENUM, BAFFLE, EXHAUST DUCT, AND SABOT TRAP
3. VELOCITY MEASUREMENT
4. TEST SECTION
5. RANGE COVER & BACKSTOP

Figure 3. Impact Mechanics Laboratory – Floor Plan

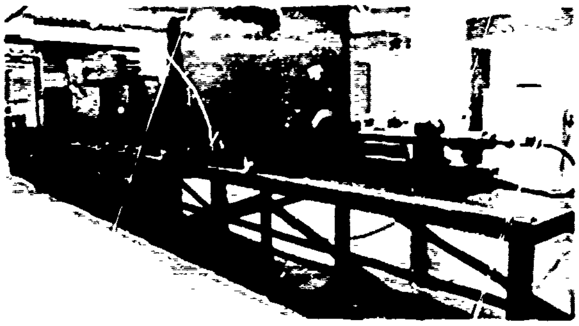


Figure 4. Impact Mechanics Laboratory – No. 2 Test Range

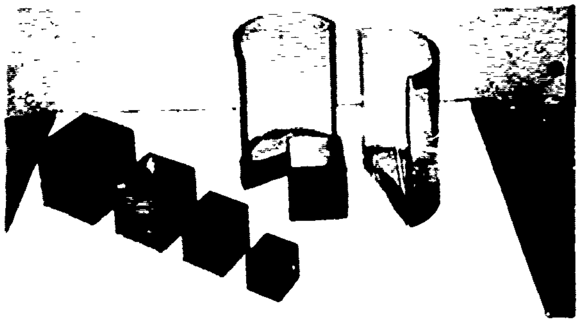


Figure 5. Simulated Engine Burst Fragments

Figure 6. Test Specimen in Range

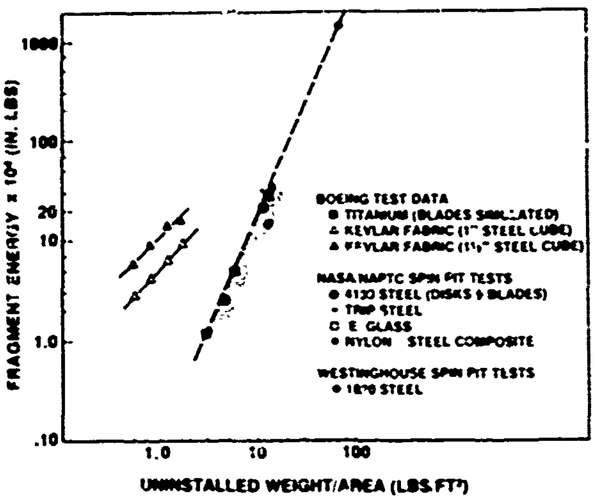


Figure 7. Containment Performance

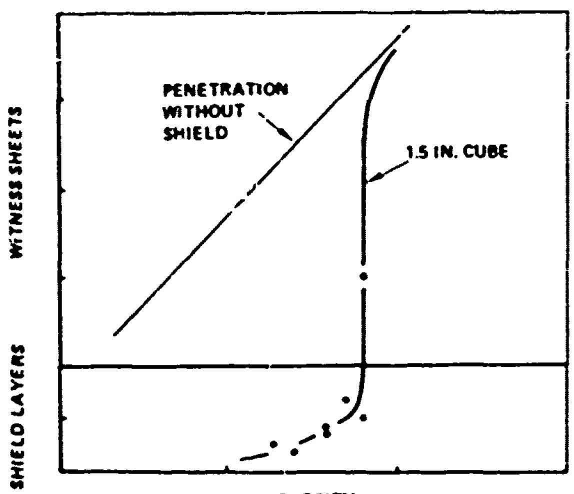


Figure 8. Test Data

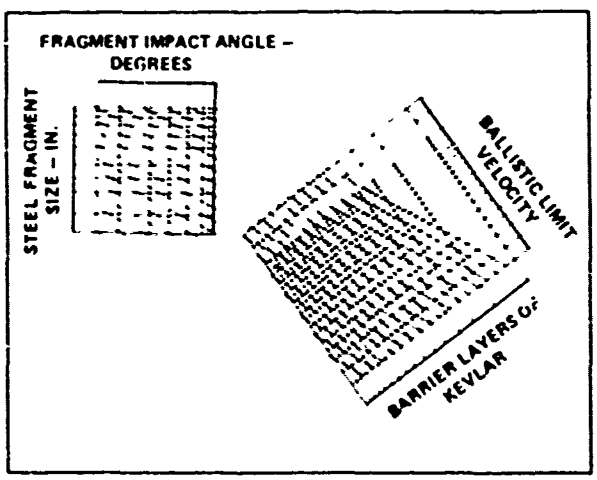


Figure 9. Empirical Engine Burst Containment Model

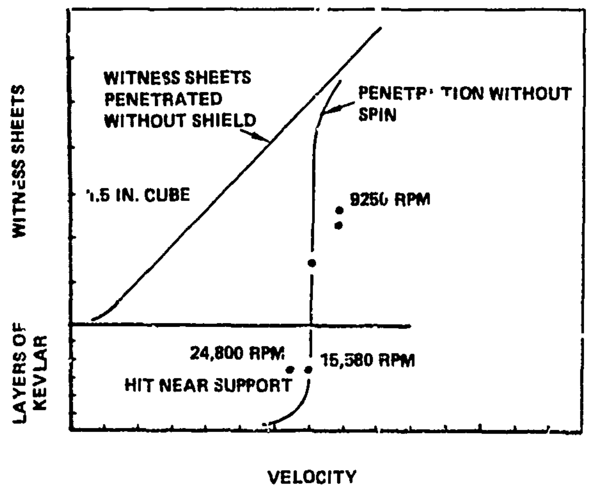


Figure 10. Effect of Spin

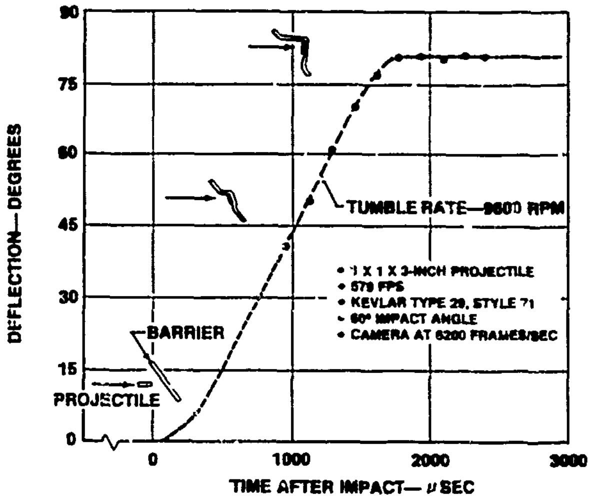


Figure 11. Tumbling of Long Projectiles

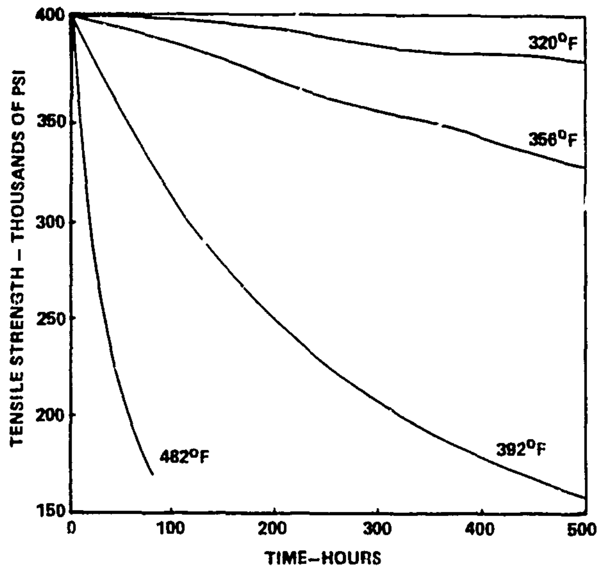


Figure 12. Temperature Effects – Static Loading

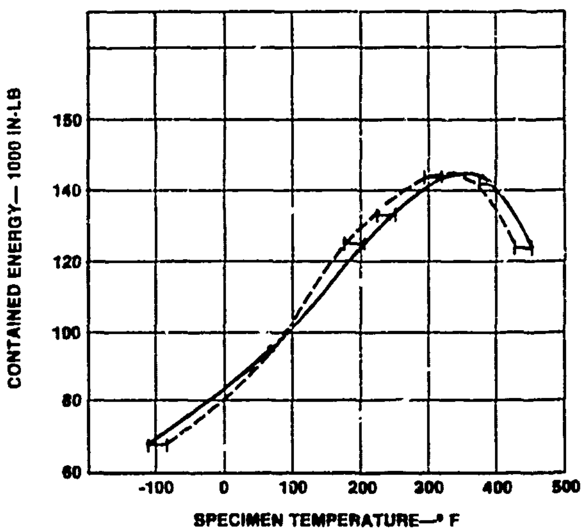


Figure 13. Effect of Temperature

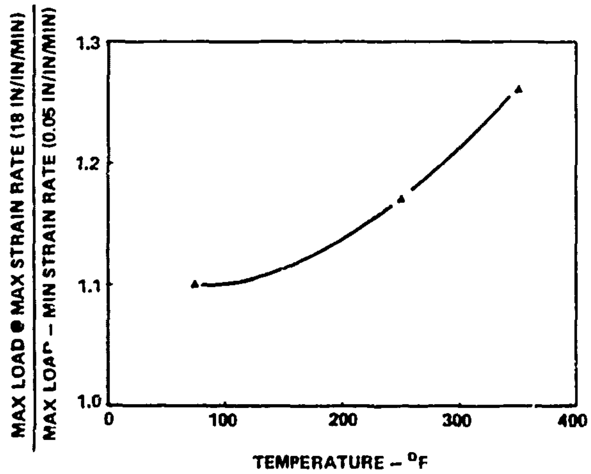


Figure 14. Temperature/Strain Rate Effects

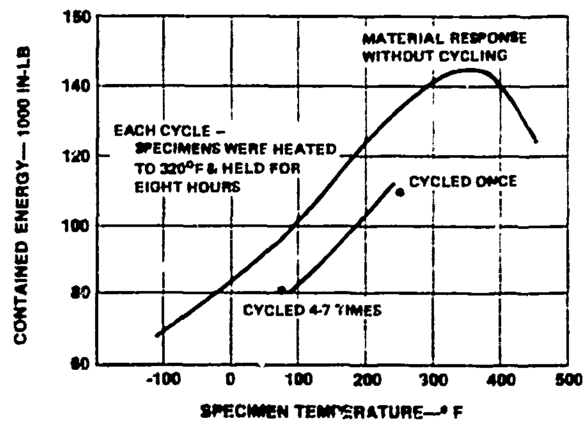


Figure 15. Temperature Cycling Effects

FINITE ELEMENT APPLICATIONS TO BATTLE DAMAGED STRUCTURE

by
Dr. Pao C. Huang, Consultant
Naval Surface Weapons Center
White Oak Laboratory
Silver Spring, Maryland 20910
United States of America

Summary

This paper introduces a "Patching Technique" for the development of a finite element model truly representing a battle-damaged aircraft. The applications of preprocessors PING and BING to the automatic generation of input data for NASTRAN analyses are also briefly shown. Finally, the importance of modeling technique is addressed.

(1) INTRODUCTION

The utilization of the finite element method in the design and analysis of a complex missile structure is an important step toward an optimized system. The great speed and precision of these techniques permit a missile to be thoroughly and repeatedly analyzed and modified, providing a more efficient weapon system. These same techniques are perfectly applicable to the structural vulnerability analysis of a battle-damaged vehicle which, in general, has a complicated configuration and requires detailed stress and deformation data. However, the success of this computer approach depends largely on the modeling technique used to develop a finite element model which accurately simulates the real structure.

In addition, the generation of such a model and its associated data output must be quick, economical, and routinized.

(2) FINITE ELEMENT PROGRAM - NASTRAN

NASTRAN, a general purpose finite element program for structural analysis developed by NASA, can be used as an example of a program for which data generation can be an overwhelming task. NASTRAN is versatile and applies to a large class of static and dynamic problems as follows:

a. Static response to concentrated and distributed loads, thermal expansion, and enforced deformation
b. Dynamic response to transient loads and random excitation
c. Determination of real and complex eigenvalues for use in vibration analysis and stability analysis.

However, preparing NASTRAN input for a complicated problem is a large effort in itself. It includes the layout of a grid mesh; calculations of grid point locations; generation of element properties and their connections to grid points; preparation of input sheets; and, finally, punching of input cards. All this work is extremely time consuming and requires the effort of a team of specialists. Furthermore, possible occurrences of human errors together with unavoidable redesign cycles would make the analysis formidable.

To remedy these difficulties, special input generation programs have been developed by the Naval Surface Weapons Center, White Oak Laboratory to automatically generate finite element models and their associated NASTRAN input for missile structures.

(3) PREPROCESSORS FOR NASTRAN

A Planform Input Generator (PING, [reference 1] which can rapidly develop a finite element model for an arbitrary wing planform of a missile, and a Body input Generator (BING) [reference 2] which performs the same function for any type of missile shell body are currently operational at NSWC/WOL. Utilizing these two preprocessors, a complete missile such as shown in Figure 1 can be easily and quickly generated for rigorous structural analyses. These two preprocessors contain many useful features which can be utilized to facilitate the development of a model to truly simulate a real missile.

The efficiency of PING is demonstrated in Figure 2 where a finite element model of a double wedge, solid, sweptback wing is shown as an example. This finite element model has 277 grid points, 260 plate elements, and 1400 degrees of freedom. PING was employed in the development of this model. It only took five manhours and a few seconds of computer time to produce 1137 input cards for NASTRAN analysis.

Without PING it would take at least 360 manhours to produce the same number of cards manually. The capability of developing a finite element model rapidly and economically

is an essential requirement for such complicated work as the vulnerability study of battle damaged structures.

Figures 3 to 8 show some of the sample finite element models developed by PING and BING. Figure 3 demonstrates the useful feature of a mixed mesh which can be used to reduce the degrees of freedom in less important areas. Figure 4 shows a model of a curved delta wing. Figure 5 illustrates how patches with a circular or elliptical hole can be used with a finer mesh around the hole for more detailed stress distribution. Figure 6 shows a wing with an elliptical hole which can be developed in two stages. First, a wing model without hole is developed and the elements around the hole are removed; then a patch with the hole can be developed to fit in the opening. Figure 7 shows a complicated but realistic missile body generated by BING. It has a nose cone and a cylindrical shell with an engine housing. Figure 8 shows a finite element model of a BQM 34A wing. This built-up wing has three spars connecting two curved panels. Again, a mixed mesh is used in the wing panels to reduce the degrees of freedom without sacrificing the accuracy in the important wing root area.

Using the preprocessors and NASTRAN, reliable analytical results can now be obtained easily and rapidly. Figure 9 shows the good correlation of the theoretical and experimental data. The latter were provided by the Naval Research Laboratory from a complete vibration test of the actual missile. The theoretical results were obtained by NASTRAN on a finite element model developed by PING and BING. It only took 40 manhours to complete the vibration model and 1200 seconds of CDC 6500 computer time to obtain the first six vibration modes. With these powerful analytical tools, elaborate structural analysis certainly becomes practical in the development of a complicated missile system.

(4) PATCHING TECHNIQUE

On a demanding task such as the vulnerability study of battle damaged structures, precise stress data around the damaged area will be required to determine the possibility of crack propagation which may lead to catastrophic failure. Finite element analysis techniques will be of great value in furnishing detailed information for such a study. Therefore, an elaborate finite element model must be developed to accurately represent the damaged structure. Using PING, this task can be easily achieved. Figure 10 shows the procedure for the development of a damaged wing structure. First, a finite element model of the undamaged wing must be generated and the plate elements around the damage removed. Then patches of damaged components having smaller plate elements can be generated to fit the cutout. Finally, these patches are inserted into the proper locations to complete the finite element model for the damaged wing. This modeling procedure is designated as the "Patching Technique". The common gridpoints on the cutout boundaries are not joined by compatibility conditions but by using a common gridpoint number, therefore, no constraint equations are required. This feature not only eliminates many input data cards, but also yields a much better finite element model.

(5) ANALYSES OF BATTLE DAMAGED STRUCTURES

A damaged BQM 34A wing was analyzed by NASTRAN under 1g loading. The finite element model of the undamaged wing had 846 grid points, 849 plate elements, and 4602 degrees of freedom. This model not only took into account the curvatures of the skin panels, but also the varying skin thickness. Five PING runs and approximately 64 manhours were taken to complete this job. The damaged wing had a slot 1.5 inches wide in the upper skin panel and extended five inches diagonally inward from the front spar to a point where the middle spar cap was completely cut. In addition, all three spars were damaged to different degrees. Using the patching technique, the finite element model for this damaged version was quickly generated by removing elements and adding patches. The final model is shown in Figure 11. The NASTRAN analyses showed significantly higher stresses in the root area of the damaged wing than those in the corresponding region of the undamaged wing. However, the most critical point was found at the slot tip with a peak stress of 10,000 psi as indicated in the plot of iso-stress-lines. The actual damaged wing was tested to destruction, which occurred at a 3g loading. A crack was first formed at the tip of the slot then propagated toward the wing root at the rear spar. This was adequately predicted in the stress contour plot whereby a peak stress of 30000 psi was obtained at 3g level; a value which was thought to be the strength of the material at that state.

The structural response of a damaged semimonocoque fuselage was analyzed from a model by the same patching technique. A vertical slot between the second and third frames near the tail end was cut in the fuselage skin. The cut extended from the crown down to a point at 108 degrees on each side. The patch had a width covering the last three bays of the fuselage and a circumferential length longer than that of the slot. As can be seen in Figure 12, much smaller elements are used in the patch especially around the tip region where high stress concentration is anticipated. This finite element model was subsequently analyzed by NASTRAN for an 1g load condition. Proper resultant forces were placed on the four cut boundaries to transmit air pressures from the nose, wings, and tail assembly which were omitted in this truncated fuselage. Stress concentrations were found around the slot tip area with sufficient intensity such that a crack would form at this point. Catastrophic failure seems certain to occur because there is no crack arresting structural member in the propagation path between frames, and the peak stress of 26000 psi shown in Figure 13 would increase rapidly as the crack enlarges.

To demonstrate the importance of the patching technique which provides stress concentration data, another analysis was made on a model obtained simply by removing the plate elements between the two frames to simulate the damage inflicted on the fuselage. This simple model, Figure 14, had a cutout wider than the slot but was bounded on four sides by smooth edges. NASTRAN analysis revealed much higher stresses than those of the undamaged model, however, no danger could be detected for any catastrophic failure in this analysis. This contradictory conclusion, of course, was not totally unexpected, especially when the simple model had a structurally sound configuration. However, it did point out the danger of under-modeling and the importance of a true simulation.

The study of structural vulnerability of battle-damaged aircraft by projectile hits can be conveniently treated in two phase. In the impact fracture phase damage criteria of instantaneous failure, i.e. the upper bound of vulnerability, are of interest. Then the assessment of local damages to the structure must be determined for subsequent survival analyses. The prediction methods in these areas are inadequate at the present time, however, some guidelines are available for a quick estimate. In the continued flight phase where residual strength, loss of control, dynamic and aerodynamic instabilities are a concern, the finite element techniques become extremely valuable. To attack these problems two distinct finite element models should be employed. A "Static Model" with sufficient damage details can be developed for residual strength analysis while a "Kinematic Model", being much simpler than the former, can be used in the analyses of structural response. The kinematic model is definitely the cheaper one to run, yet would yield sufficiently accurate results in stiffness or dynamic analysis. For completeness, many different analyses must be performed on a large structure, these models must be carefully designed for optimization in terms of accuracy and economy.

(6) CONCLUSION

Using the preprocessors PING and BING together with NASTRAN, finite element techniques can now be applied easily and rapidly to the study of structural vulnerability. Precise response data can be generated, analyzed for the residual strength and performance of the damaged vehicle.

Patching technique has been applied to the development of a finite element model for a damaged vehicle. The procedure is found convenient and efficient. Good stress concentration data have been obtained.

Modeling to truly represent a damaged vehicle is an important task. It should not be over- or under-designed for economical or accuracy reason.

References

1. Huang, Pao C., and Matra, John P., Jr., "Planform Input Generator (PING), A NASTRAN Preprocessor for Lifting Surfaces-Theoretical Development, User's Manual, and Program Listing," NOLTR 73-109, Naval Ordnance Laboratory White Oak, Silver Spring, MD, Dec 1973

2. Huang, Pao C., and Matra, John P., Jr., "Missile Body Input Generator (BING), A NASTRAN Preprocessor, Theoretical Development, User's Manual, and Program Listing," NSWC/WOL/TR 75-9, Naval Surface Weapons Center, White Oak Laboratory, Silver Spring, MD, Mar 1975

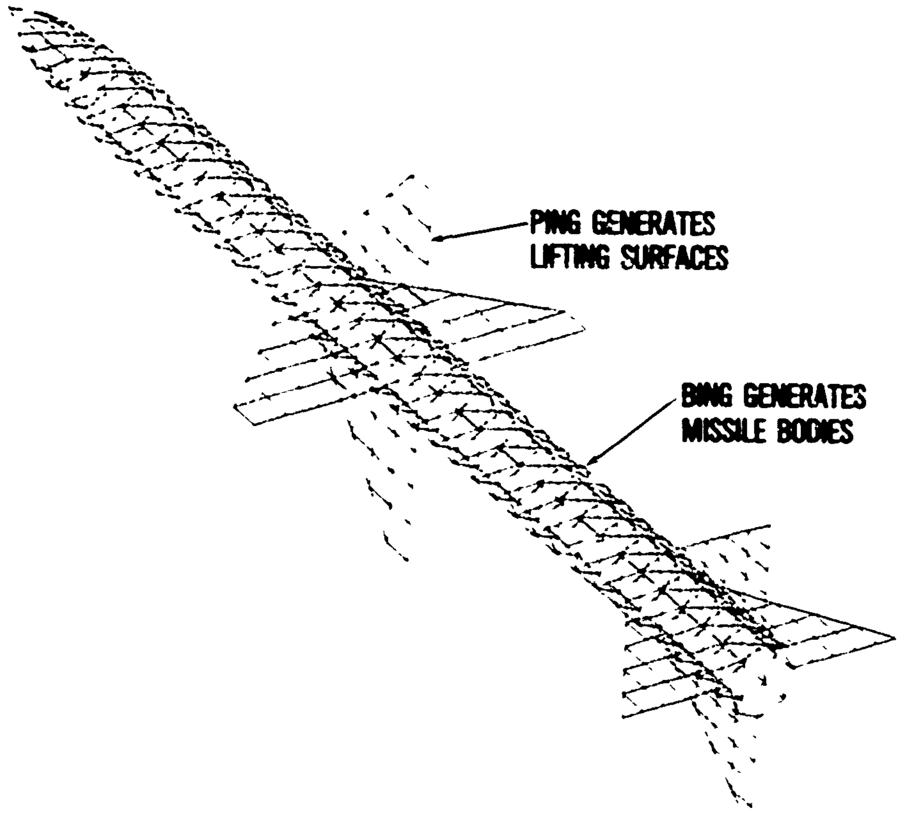


FIG. 1 A COMPLETE FINITE ELEMENT MODEL FOR ELABORATE STRUCTURAL ANALYSIS

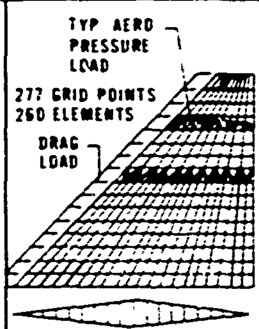
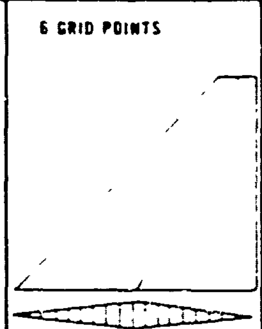
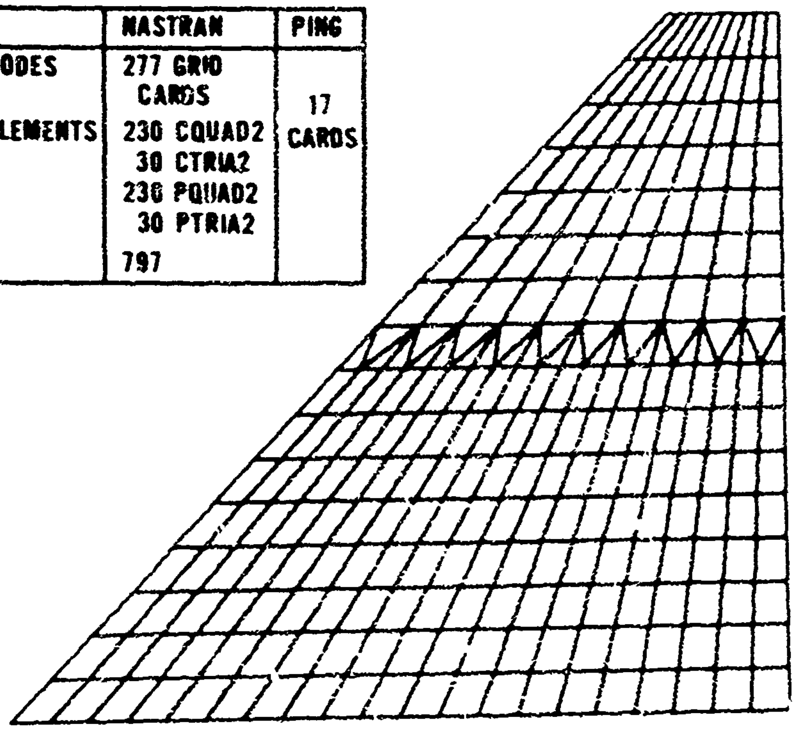
DATA GENERATION	NASTRAN		PING/NASTRAN	
BASIC PLANFORM INFORMATION I OVERALL DIMENSIONS II MESH LAYOUT III AERO DATA				
	TIME (MAN HOUR)	NO OF CARDS	TIME (MAN HOUR)	NO OF CARDS
COMPUTATION	280	0	3	0
WRITE-UPS IN PROGRAM FORMATS	40	0	1	0
CARD PUNCHING	24	1137	5	29
VERIFICATION AND CORRECTION (10% EST.)	16	114	5	3
INPUT CARDS REQ'D FOR NASTRAN		1137		1137
CARDS MANUALLY PUNCHED		1251		32
TOTAL TIME REQUIRED	360		5	

FIG. 2 EFFICIENCY OF PING/NASTRAN

REQUIRED INPUTS CARDS

	NASTRAN	PING
NODES	277 GRID CARDS	17 CARDS
ELEMENTS	230 CQUAD2 30 CTRIA2 230 PQUAD2 30 PTRIA2	
	797	



(1385 DEGREES OF FREEDOM)

FIG. 3 SPARROW III SOLID WING PLAN FORM

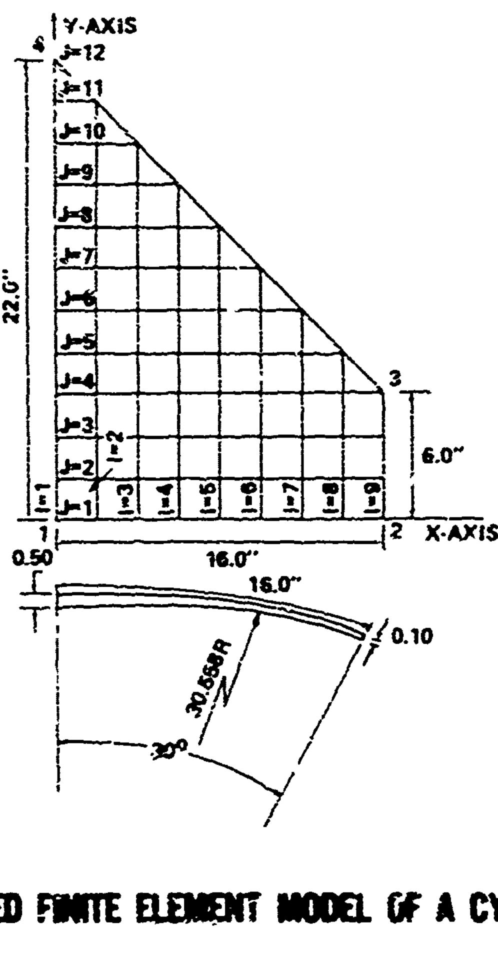


FIG. 4 PLANNED FINITE ELEMENT MODEL OF A CYLINDRICAL WING

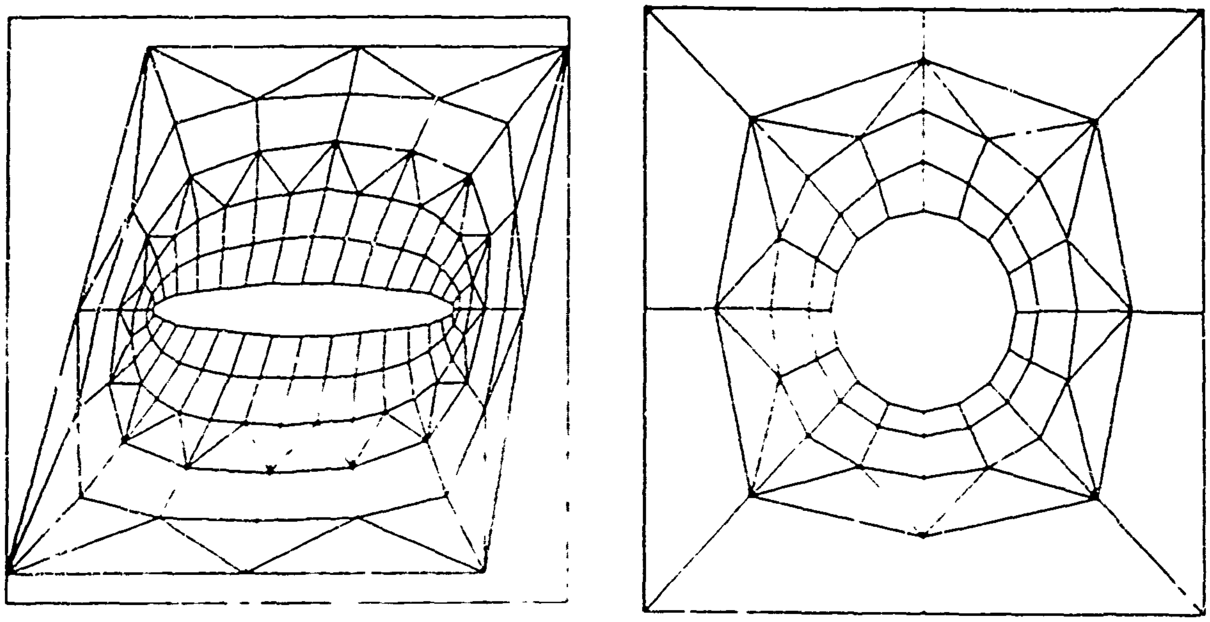


FIG. 5 SAMPLE PATCHES DEVELOPED BY PING

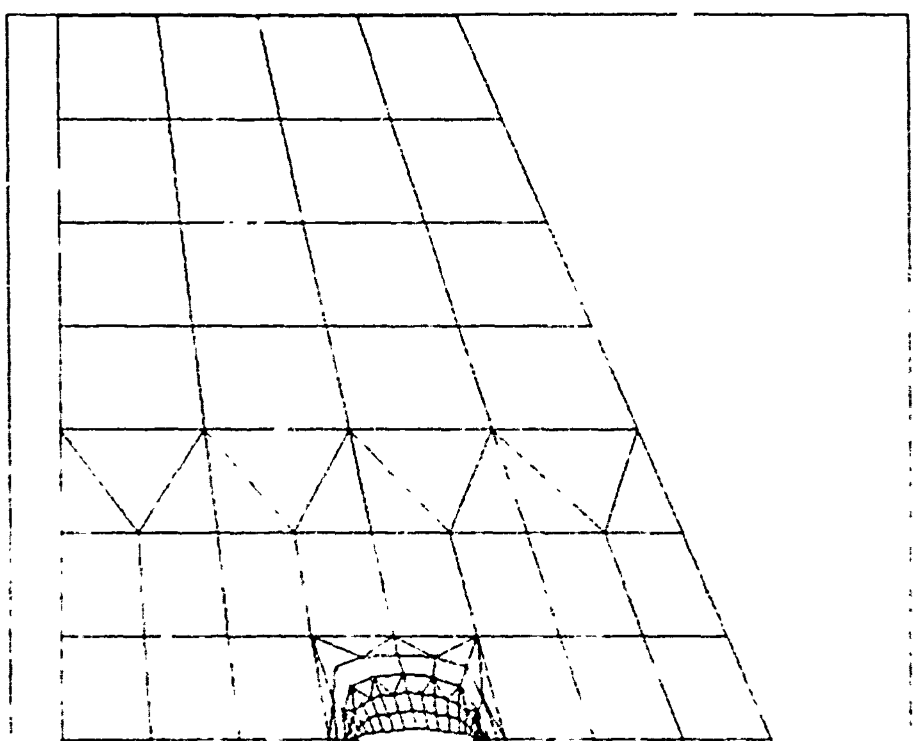


FIG. 6 WING WITH ELLIPTICAL HOLE

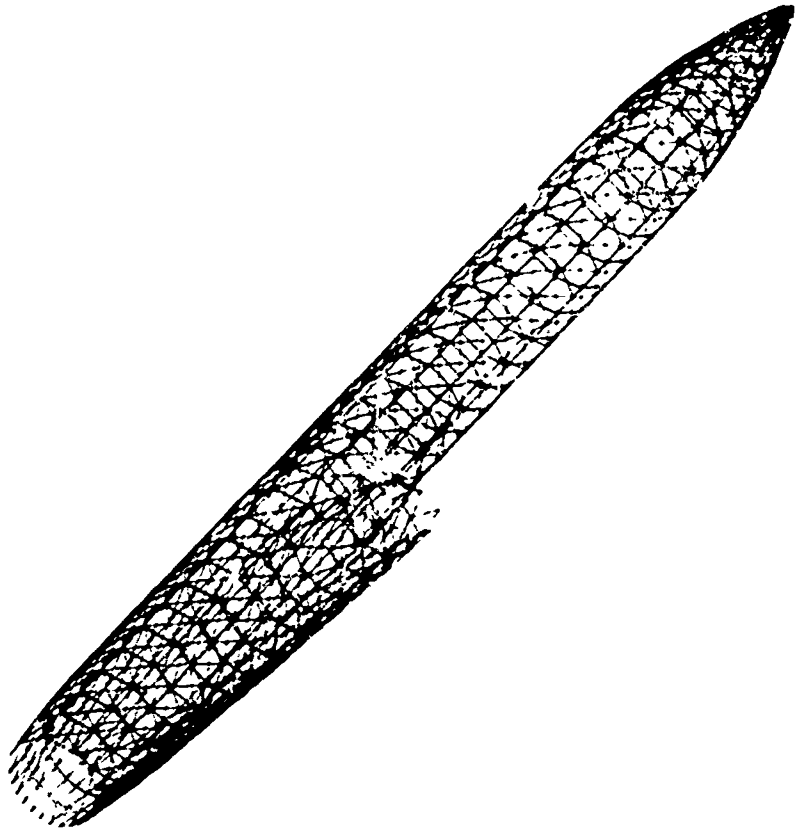


FIG. 7 FUSELAGE WITH ENGINE HOUSING DEVELOPED BY BING

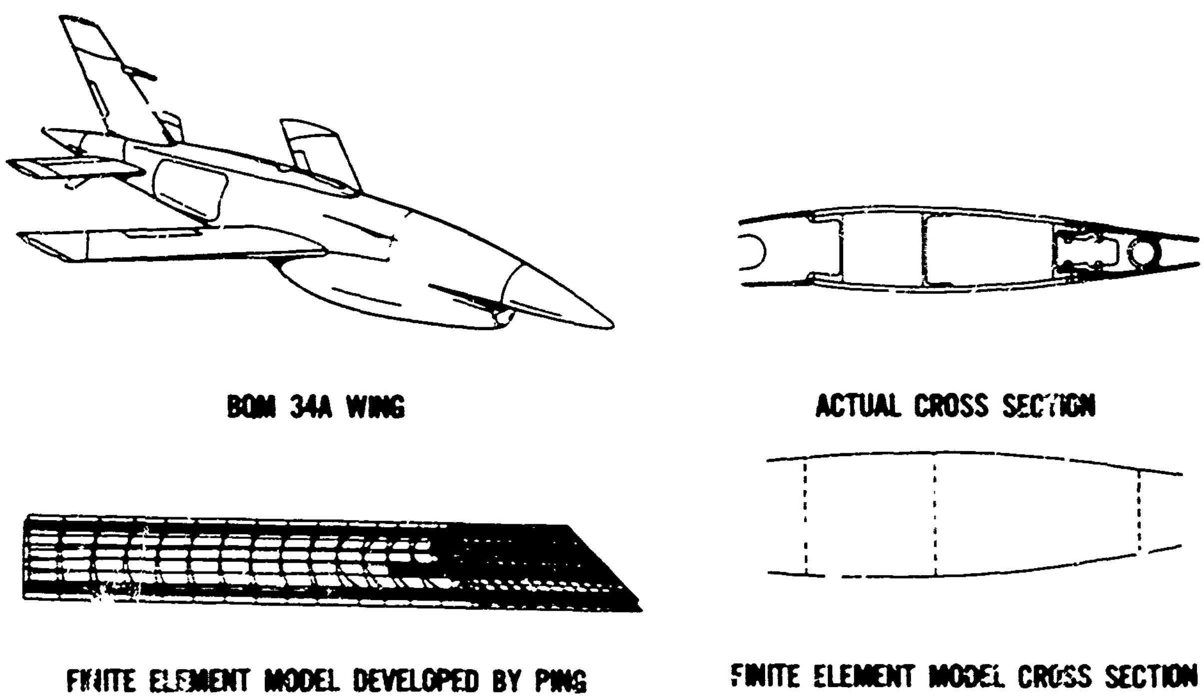


FIG. 8 FINITE ELEMENT MODEL OF BUILT-UP WING DEVELOPED BY PING

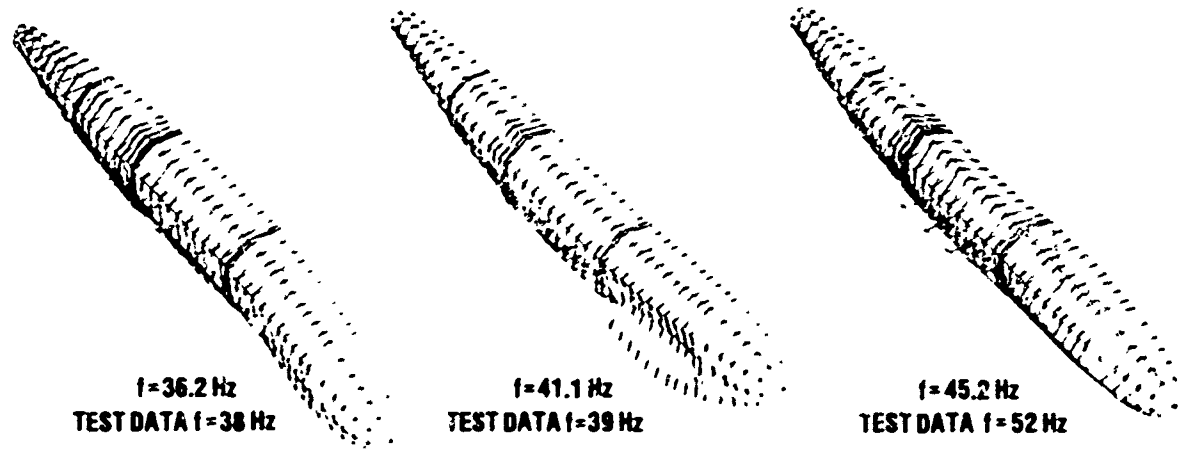
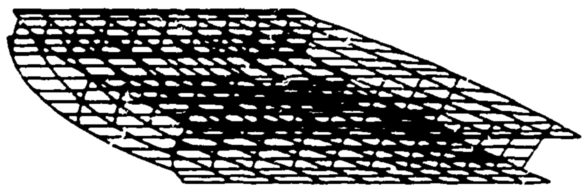
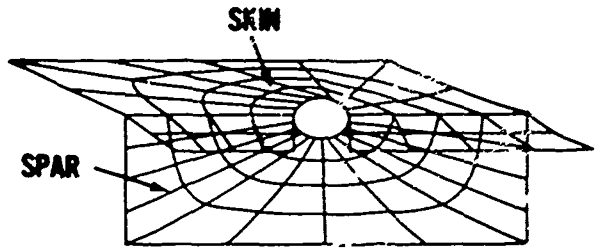


FIG. 9 COMPARISON OF THE THEORTICAL AND EXPERIMENTAL DATA OF A VIBRATION MODEL DEVELOPED BY PING AND BING



FINITE ELEMENT MODEL OF WING ROOT SECTION GENERATED BY PING



PATCH OF DAMAGED COMPONENTS GENERATED BY PING TO FIT THE CUT-OUT

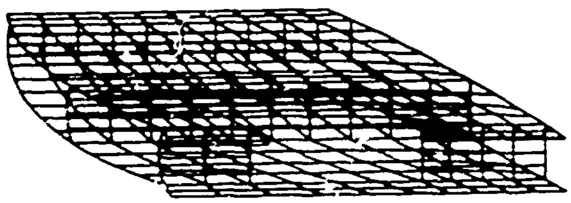
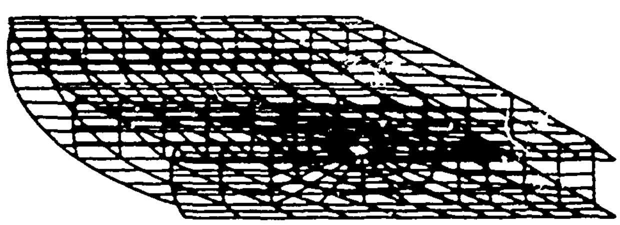


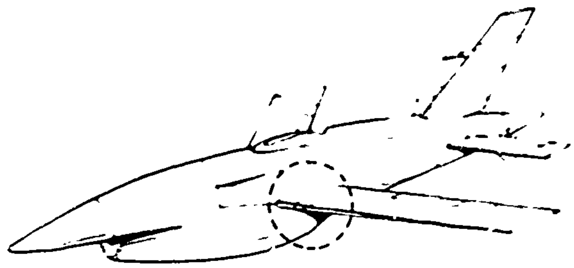
PLATE ELEMENTS AROUND DAMAGED AREA REMOVED



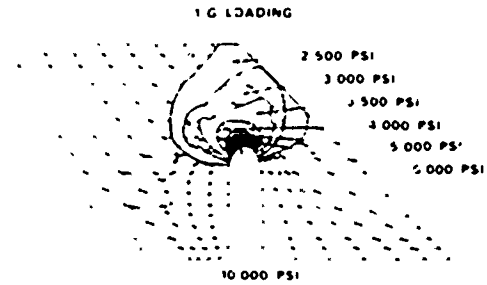
COMPLETED FINITE ELEMENT MODEL FOR A DAMAGED WING

FIG. 10 DEVELOPMENT OF FINITE ELEMENT MODEL FOR A DAMAGED WING WITH PING

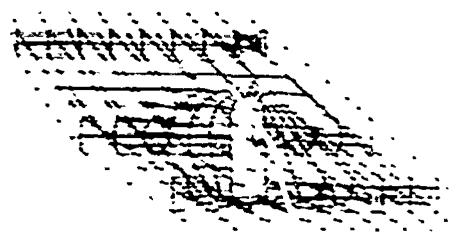
BQM 34A DRONE



ISO-STRESS-LINES FOR DAMAGED COVER
OF THE BQM 34 A WING



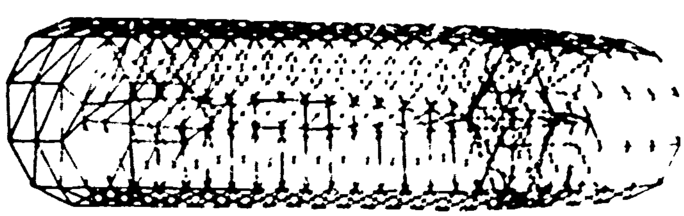
FINITE ELEMENT MODEL OF DAMAGED BQM 34 A WING



BQM 34 A DAMAGED WING COVER

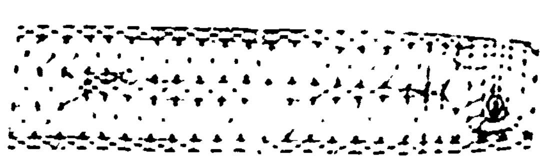
CRACK DUE TO 3G LOAD

FIG. 11 VULNERABILITY STUDY OF A DAMAGED MISSILE WING



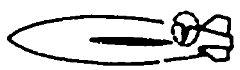
FINITE ELEMENT MODEL OF A SECTION OF A FUSELAGE

DAMAGE PATCH FOR FUSELAGE

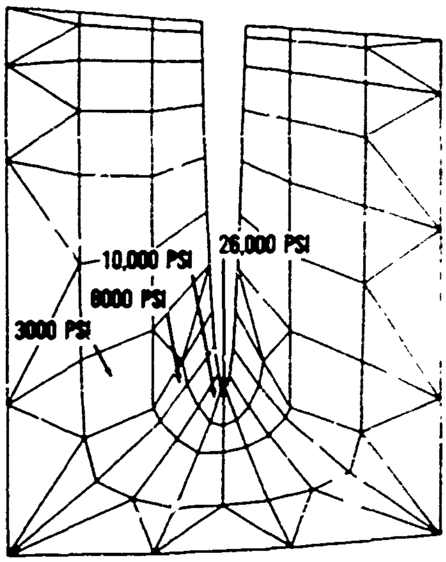


FINITE ELEMENT MODEL OF
A DAMAGED FUSELAGE

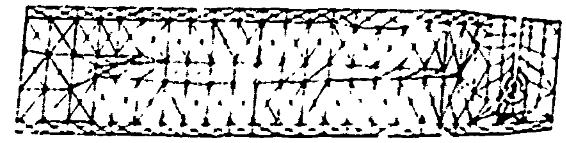
**FIG. 12 DEVELOPMENT OF FINITE ELEMENT MODEL
FOR A DAMAGED FUSELAGE WITH BING**



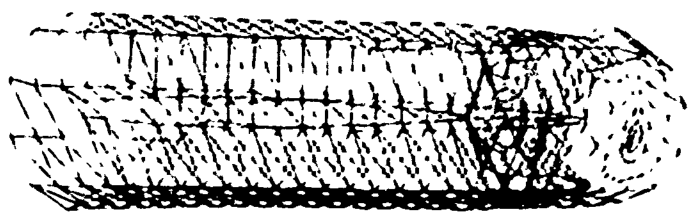
VERTICAL CUT BETWEEN FRAMES



HIGH STRESS AT DAMAGED TIP INDICATES CRITICAL CONDITION FOR CRACK PROPAGATION



ANALYTICAL MODEL GENERATED BY BING FOR NASTRAN ANALYSIS



DISTORTION OF DAMAGED AREA UNDER 1-G LOAD CONDITION

FIG. 13 VULNERABILITY STUDY OF A DAMAGED MISSILE BODY

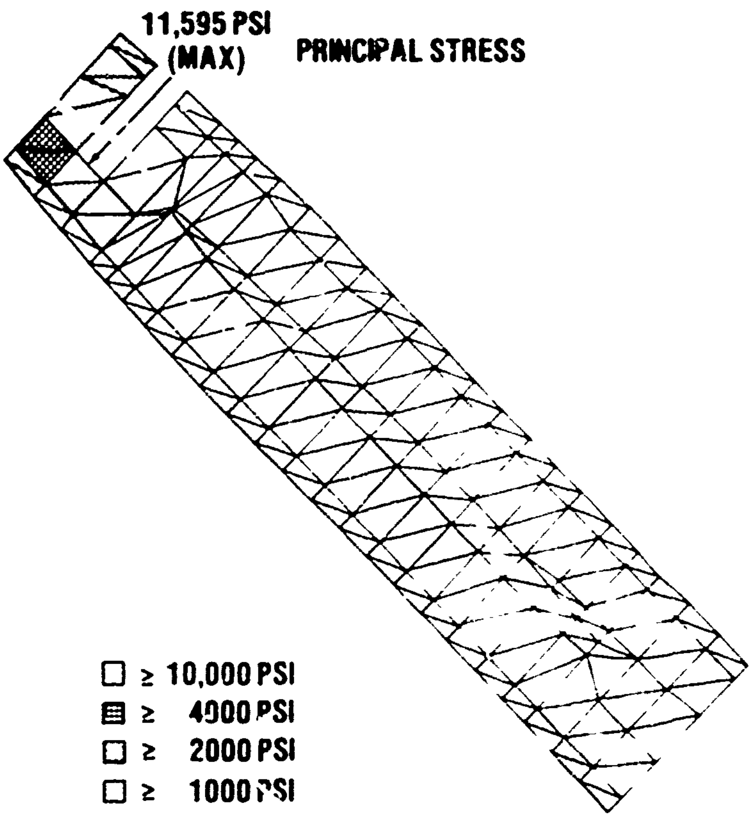


FIG. 14 DAMAGE MODEL WITH SMOOTH SIDES

4

AGARD

NATO OTAN

7 RUE ANCELLE · 92200 NEUILLY-SUR-SEINE

FRANCE

Telephone 745.08.10 · Telex 610176

DISTRIBUTION OF UNCLASSIFIED AGARD PUBLICATIONS

AGARD does NOT hold stocks of AGARD publications at the above address for general distribution. Initial distribution of AGARD publications is made to AGARD Member Nations through the following National Distribution Centres. Further copies are sometimes available from these Centres, but if not may be purchased in Microfiche or Photocopy form from the Purchase Agencies listed below.

NATIONAL DISTRIBUTION CENTRES

BELGIUM
Coordonnateur AGARD - VSL
Etat-Major de la Force Aérienne
Caserne Prince Baudouin
Place Dailly, 1030 Bruxelles

CANADA
Defence Scientific Information Service
Department of National Defence
Ottawa, Ontario K1A OZ2

DENMARK
Danish Defence Research Board
Østerbrogades Kaserne
Copenhagen Ø

FRANCE
O.N.E.R.A. (Direction)
29 Avenue de la Division Leclerc
92 Châtillon sous Bagneux

GERMANY
Zentralstelle für Luft- und Raumfahrt-
dokumentation und -information
D-8 München 86
Postfach 860880

GREECE
Hellenic Armed Forces Command
D Branch, Athens

ICELAND
Director of Aviation
c/o Flugrad
Reykjavik

ITALY
Aeronautica Militare
Ufficio del Delegato Nazionale all'AGARD
3, Piazzale Adenauer
Roma/EUR

LUXEMBOURG
See Belgium

NETHERLANDS
Netherlands Delegation to AGARD
National Aerospace Laboratory, NLR
P.O. Box 126
Delft

NORWAY
Norwegian Defence Research Establishment
Main Library
P.O. Box 25
N-2007 Kjeller

PORTUGAL
Direccao do Servico de Material
da Forca Aerea
Rua de Escola Politecnica 42
Lisboa
Attn. AGARD National Delegate

TURKEY
Department of Research and Development (ARGE)
Ministry of National Defence, Ankara

UNITED KINGDOM
Defence Research Information Centre
Station Square House
St. Mary Cray
Orpington, Kent BR5 3RE

UNITED STATES
National Aeronautics and Space Administration (NASA),
Langley Field, Virginia 23365
Attn Report Distribution and Storage Unit

THE UNITED STATES NATIONAL DISTRIBUTION CENTRE (NASA) DOES NOT HOLD STOCKS OF AGARD PUBLICATIONS, AND APPLICATIONS FOR COPIES SHOULD BE MADE DIRECT TO THE NATIONAL TECHNICAL INFORMATION SERVICE (NTIS) AT THE ADDRESS BELOW

PURCHASE AGENCIES

Microfiche or Photocopy
National Technical
Information Service (NTIS)
5285 Port Royal Road
Springfield
Virginia 22151, USA

Microfiche
Space Documentation Service
European Space Agency
114, Avenue Charles de Gaulle
92200 Neuilly sur Seine, France

Microfiche
Technology Reports
Centre (DTI)
Station Square House
St. Mary Cray
Orpington, Kent BR5 3RF
England

Requests for microfiche or photocopies of AGARD documents should include the AGARD serial number, title, author or editor, and publication date. Requests to NTIS should include the NASA accession report number. Full bibliographical references and abstracts of AGARD publications are given in the following journals

Scientific and Technical Aerospace Reports (STAR),
published by NASA Scientific and Technical
Information Facility
Post Office Box 8757
Baltimore/Washington International Airport
Maryland 21240, USA

Government Reports Announcements (GRA),
published by the National Technical
Information Services, Springfield
Virginia 22151, USA

Printed by Technical Editing and Reproduction Ltd
Harford House, 7 9 Charlotte St, London W1P 1HD

ISBN 92-835-1224-3